SAFETY TRAINING FOR RIGGING USING VIRTUAL REALITY

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ABSTRACT: *Tower and Mobile Cranes are some of the most commonly used heavy equipment in all construction sites, and any crane failures could lead to significant human and monetary losses. Moreover, rigging configuration determination is a critical task that requires the rigging crew to have significant experience and knowledge of various failure modes that can be encountered when performing lifting operations. However, despite the criticality of training riggers, there has yet to be a comprehensive tool used to train and guide inexperienced riggers, and hence, more practical tools are needed. This paper proposes a framework for using Virtual reality (VR) and simulation to train riggers to identify the optimal rigging configurations based on the lift type and the external conditions. Through 3D modeling, the critical components of the rigging system are modeled to accurately simulate the rigging system and their performance when faced with critical loading scenarios. The developed framework is expected to allow inexperienced riggers to identify critical failure modes and enhance construction operations' overall safety performance and productivity. Furthermore, several scenarios are assessed based on historical evidence for rigging configuration failures, and the efficiency of the training tool is assessed through real-life scenarios and tests.*

KEYWORDS: *Crane Operations, Lift Planning, Rigging, Safety, Training, Virtual Reality.*

1. INTRODUCTION

Globally, construction and industry-related incidents account for significant human and material losses; as a result, the construction industry is considered one of the most hazardous industries for workers. According to the Occupational Safety and Health Administration (OSHA,2020), in 2019, 1061 worker fatalities occurred in the construction industry, accounting for 20% of deaths in all industries. A contributing factor to the increased number of incidents is the use of heavy pieces of equipment, where many fatal injuries were a result of using heavy equipment." For instance, in Australia, Safe Work Australia 2019 reported that there are, on average, 240 serious injury claims reported from crane safety incidents". Furthermore, the current construction trends, such as Off-Site construction (Lingard et al.,2021), are gaining more traction for project execution. Moreover, Off-site construction is heavily reliant on cranes, and thus, an increase in crane usage is inevitable. Fatal incidents would increase exponentially with the increased use of crane construction projects. Thus, it is critical to understand the underlying reasons for incidents related to crane operations and to develop the necessary tools required to mitigate the number of incidents.

Much research has been conducted to understand the causes of crane incidents. (Milazzo et al ,2016) Analyzed 937 crane incidents and identified that the leading cause of incidents for different cranes is overturning and collapse, mainly due to structural failures caused by overloading. Another contributing factor is human error (Milazzo et al., 2016) found that one-third of crane incidents were triggered by human error, resulting in either weight underestimation or improper operation of the crane. (Lingard et al.,2021) Identified that the main types of incidents in crane operations are those related to electrocutions and tip-over incidents. On one side, electrocution incidents result from improper planning, unsafe working conditions, and human negligence. On the other hand, Tip-over incidents are mainly caused by overloading, loss of center of gravity, and outrigger failure. Finally, (Tam and Fung,2011) identified four main factors causing safety incidents in crane operations: negligence and misjudgment, inadequate training, subcontracting, and pressure from deadlines. Thus, to mitigate crane-related on-site incidents, it is necessary to eliminate human error, avoid overloading and structural failures. (Zhang et al.,2023) the overturning and loss of center of gravity can be prevented by securing the lifted loads; this prevention is a major duty of rigging personnel whose performance can be enhanced through adequate training.

Training has been a primary focus for crane operations, where many tools were used to provide operators, riggers, and signalers with the proper procedure to perform lifts. In most cases, only traditional training methods were used, which centered around textbooks, video tutorials, and a limited amount of hands-on experience, which is less immersive. (Wu et al.,2020) argues that learning by doing has been recognized as a more effective training method. Furthermore, they argue that traditional lecturing courses are less effective in transmitting learning

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knowledge. Luckily, recently, with the rise of VR, more research is being conducted to understand the impact of VR training on construction workers. For instance, (Joshi et al., 2021) used VR technology for safety training in the precast/prestressed concrete industry and found that knowledge gained through traditional methods is lower than that gained from VR training methods. (Song et al.,2021) developed a VR crane operator training module and reported that VR training effectively enhances crane control skills competence.

Crane operations and VR training procedures are scarcely represented in the literature, where only a limited set of works were published regarding crane-related operations and VR training. Previous works focused on using VR to visualize crane lifts and hazard identification through clash detection. (Shringi et al.,2022) for instance, developed a hazard identification training model for crane operators, which focused mainly on tower cranes. (pooladvand et al, 2021) Used interactive VR to evaluate mobile crane lifts. While (Song et al, 2021) developed a VR crane operator training module but did not take into consideration the rigging personnel training. Regarding rigging, (Zhang et al., 2023) developed a collaborative training model for crane operators, riggers, and signallers. However, the main focus was on collaboration between the different project participants. Furthermore, for rigging, only a semi-immersive CAVE system was utilized for collaboration and communication between the different project participants taking part in operating, and guiding cranes. However, a training system which takes into consideration the elaborate and complex properties of rigging components is yet to be tackled by any work.

Thus, this work identifies the need for developing a fully immersive and engaging tool to train riggers and mitigate on-site incidents. To do so, the authors propose a fully immersive VR-based training framework for riggers to tackle the main causes of crane-related on-site incidents. The proposed methodology is expected to improve the overall safety of crane operations as well as decrease the number of incorrect assemblies and improving the overall performance of crane related operations.

2. METHODOLOGY

The overall methodology proposed by the authors is summarized in Figure 1.

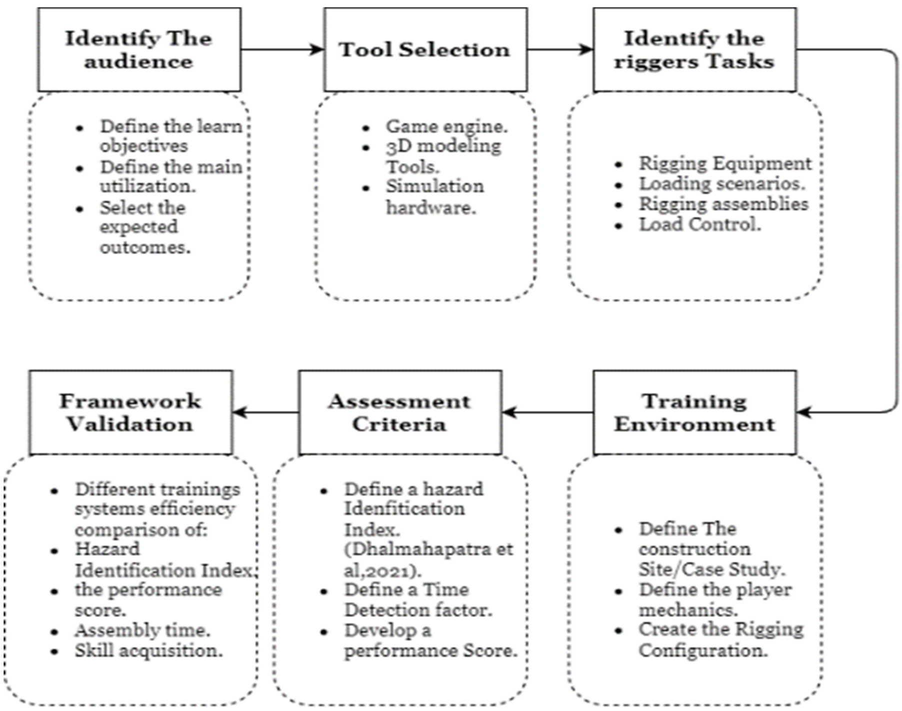

Fig. 1:Research Methodology

The initial step is to identify the audience of the VR tool. Later, tool selection is vital in any VR environment; a set of decisions are needed to select the game engine and the VR hardware to improve the overall experience. Next, the main issues encountered on-site are identified to enable the development of a realistic model capable of accurately representing the real working environment. Moreover, to assess the training progress, a set of assessment criteria is needed to estimate the trained personnel's overall performance objectively. The next step is to build the training environment by initially creating 3D models of the rigging components using 3DSMax and

SolidWorks. Then, to represent the construction site, a BIM model of a real project is exported to the VR environment, and a set of training scenarios are selected appropriately. Finally, a set of validation tools are implemented to validate the methodology, and the results are discussed.

2.1. Identify The Audience

The primary focus of this study is to utilize the Virtual Reality (VR) training tool to teach novice and inexperienced riggers the best practices for safe crane operations. The tool aims to enhance the overall safety of crane operations by addressing critical aspects such as better rigging assemblies, identification of erroneous assemblies, secure load lifting, and identification of faulty equipment. Additionally, civil engineering students seeking to learn crane operation concepts can also benefit from this tool.

2.1.1. Define the learning objectives.

The learning objectives of the training module are as follows:

- Enhancing skills in rigging assemblies: Trainees will learn how to select and assemble the appropriate slings, shackles, hooks, spreader bars, and bolts according to the specific load being lifted.
- Identifying and avoiding hazards: Trainees will be educated on identifying potential hazards during rigging operations and how to avoid accidents by adhering to safety guidelines such OSHA.
- Securing loads during lifting: Trainees will gain insights into load calculations, determining the center of gravity, and ensuring the load is securely balanced and lifted correctly.
- Detecting faulty equipment: Trainees will learn how to inspect rigging equipment prior to assembly and identify any faulty components that may compromise safety.

2.2. Tool Selection

To develop a fully functioning and accurate training module, it is first necessary to select the necessary tool to develop the module. The following sections will discuss the selected Game engine,3D modeling tools and the hardware used throughout this work, as well as the reasoning behind selecting these tools.

2.2.1 Game Engine and 3D modeling Tools

As for the game engine, Unity3D was selected due to its ease of implementation and the availability of a diverse set of libraries and tools which can be used for simulation purposes. The 3D modeling software selected are 3DS max, and SolidWorks.3DSMax was used to import and design some of the necessary components of the raining environment. While SolidWorks was used to create 3D models for the rigging components, such as the hooks, spread bars, slings, and eyebolts. Both 3D software were also chosen since they are compatible with the selected game engines, where it is advisable to use the previously mentioned software alongside a rendering software to provide a more realistic and engaging training environment.

2.2.2 Hardware Description

As for the hardware, an HTC Vive Headset was used for training. The headset was used to allow the user to explore the environment. two Wireless controllers were also used, their utility lies in allowing the user to move through the environment and interact (grab, assemble and dissemble) the relevant rigging components. The movement of the player was detected using two HTC bases. The overall system was run on a supercomputer, with an I9 CPU, and NVIDIA RTX A2000 GPU and 32Gb of RAM.

2.3. Rigger Tasks

After thorough analysis of crane operators training guides such as (ATP 2013), as well as analyzing relevant research such as (Zhang et al, 2023) works riggers tasks were identified as follows:

- check the rigging equipment, in other words, select the appropriate slings, shackles, hooks, spreader bars and bolts in accordance with the module to be lifted.
- load calculations, and center of gravity determination of the loads to be lifted.
- Rigging equipment inspection prior to assembly.
- rigging assembly, by ensuring that each component is secured and respects the angular limits.

- Load Control by ensuring the load is balanced and lifted properly throughout the lift. Ensure the center of gravity and hook are aligned.

2.4. Training Environment

In order to accurately model a construction site, and its properties. The Unity3D engine is used to develop a realistic construction site as well as the user interaction with said environment. The following section will delve into detail and discuss both the construction site and the human interaction within the environment.

2.4.1 Construction Site and Rigging Configuration

A virtual construction site was created to provide the trainees with a sense of dimensions and realism when training which can be seen in Figure 2. The site is populated with various interactable items similar to a real construction site. The rigging components and other items in the virtual training environment are modeled on 3D software with accurate dimensions and physical properties to those used in real operations. However, the interactable items the trainees can interact with, and use are mainly those required to assemble a rigging system. Additional components that are either faulty or unneeded are added to render the tasks more challenging and, eventually, more rewarding. Furthermore, to enhance immersion, audio, and interactive interfaces were used to imitate a real-life learning environment and provide an optimized training process.

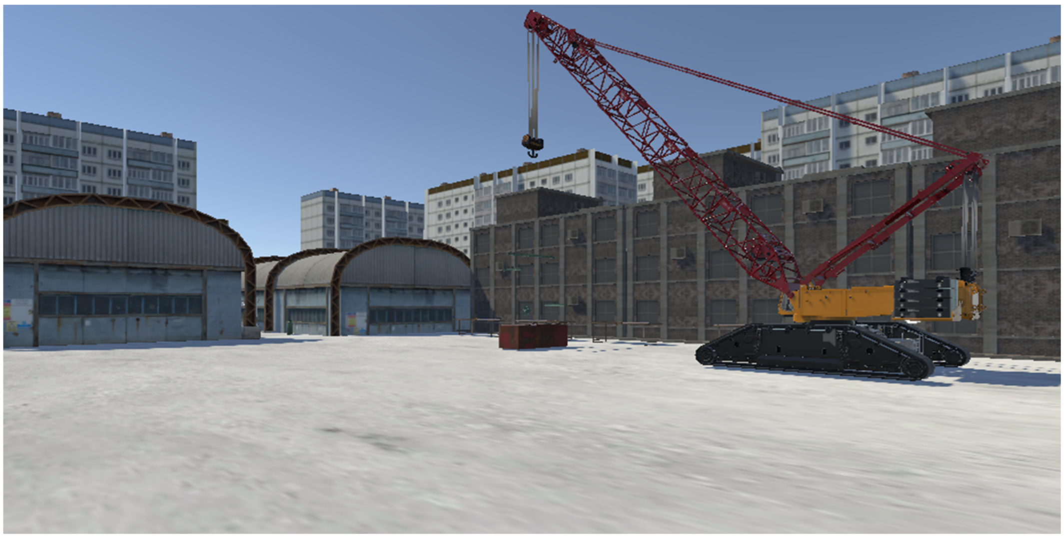

Fig. 2: Training Environment.

2.4.2 VR Controls

Replicating human interaction in a virtual environment is often a complex task, specifically when the Virtual environment is large in scale. The main difficulty encountered is regarding the locomotion system which is related to the ability to roam and use to environment.to tackle this issue, two different systems of movement are used to replicate the movement of workers on site. The first system, which is generally used in serious desktop based serious games where the user inputs the direction continuously through a touchpad. The second system is through a teleportation system, where the user can teleport to any accessible location in the construction site. The user is given the option to use one or a mixture of the systems according to their preferences. However, it is preferable to use the second system if the user is more likely to encounter VR dizziness.

As for the interaction system, the user can grab, assess, assemble, and disassemble any rigging components, which is the main feature used to create a realistic interactive training system. Finally, after assembling the rigging, the user can evaluate the efficiency and accuracy of their assembly by performing a lift. The lift is subjected to the environmental conditions present in a construction site, which are accurately replicated in the Unity environment.

2.5. Assessment Criteria

In order to assess the performance of the participants and the efficiency of their training, a hazard identification index inspired by (Dhal Mahapatra et al,2021) is used to grade and measure their performance. The scoring system identifies the primary and secondary tasks to be executed by the participant. Each task is given a score ranging from a one to three scale where one is a basic task that is fundamental but is not critical to the overall safety, and 3 is an advanced task critical to ensuring crane operations. The score system is also affected by a time factor or a time detection factor to put an emphasis on completing the tasks within the allotted time. Table 1 illustrates the different training levels and their assessment criteria.

Table 1: Training Assessment Criteria for different.

Level	Task Description	Score Range
Level 1 - Basic Task:	Fundamental actions and responsibilities contributing to the safety and smooth functioning of crane operations. These tasks require moderate skill and understanding but are not considered critical or highly complex.	1-3
Level 2 - Intermediate Task	Moderately complex actions that are more crucial to the overall safety and efficiency of the crane operations. These tasks require a higher level of skill, attention to detail, and decision-making.	4 to 7
Level 3 - Advanced Task	Critical to ensuring crane operations' utmost safety, accuracy, and effectiveness. It involves handling challenging scenarios and potential emergencies and making critical decisions promptly. These tasks demand a high level of expertise, problem-solving abilities, situational awareness and timely decision making.	8 to 10

2.6. Framework Validation

(Harris et al, 2020) defined validation as the extent to which a test, model, measurement, simulation, or other reproduction provides an accurate representation of its real life equivalent. Furthermore, (Salinas et al, 2022), defined evaluation methods as either objective or subjective.

2.6.1 Objective methods

Objective methods are those methods which evaluate efficiency based on factual data. (Salinas et al, 2022) found four main objective methods used in literature. For safety training, they are defined as follows:

- safety improvement: by comparing the behavior under training with the recommended behavior defined by safety requirements.
- performance time: measuring the time needed by a trainee to preform the required tasks, while also considering the impact of making a wrong decision. This method is used to measure the consequences of timely decision making on the overall on-site safety.
- number of errors measures the number of errors committed by the participants. And for this case study, compare the results for different groups of participants to gain a deeper understanding the VR tools impact on decreasing the number of errors made.
- measurement of vital signs: based on monitoring vital sings of trainees to understand the physical and psychological impact of stressful and dangerous scenarios on the overall performance of the trainees.

2.6.2 Subjective methods

Subjective methods are those methods which evaluate efficiency based on the trainees' feelings and preferences. (Salinas et al, 2022) mentions 4 major subjective evaluation methods which are sensory user emotions, expert analysis, user field workload and interviews and questionnaires.

Thus, and in order to validate the proposed framework, different validation techniques are used in the initial trials, both objective and subjective. As for objective methods, two validation techniques were deemed appropriate, which are performance time and number of errors, these two methods were selected to measure the learning of the trainees as well as understand the impact of timely decision making on the overall performance of crane operations. The rest of the objective methods were not used for this work; However, the developed model allows the inclusion of these methods in future studies.as for subjective methods, questionnaires and interview were used to validate the overall experience the users had when interacting with the training environment.

3. MODEL DEVELOPMENT AND TRAINING PROCEDURE

When developing the training procedure, a natural progression from more manageable tasks to more complex tasks was selected to increase the efficiency of the overall training. The training procedure was inspired by relevant training manuals such as the ATP 2013 and crane safety-related standards. The training consists of four primary levels, starting from a basic introduction to the crane safety problem. Then, a components identification module for rigging assemblies, followed by a basic assembly and secure rigging module. The training procedure is finalized with an advanced assembly and simulation concluding module. The four are explained in more detail below.

3.1 Basics Introduction

Briefly explain the importance of proper crane rigging techniques and the potential risks associated with incorrect rigging. Emphasize the need for a comprehensive training program to ensure safe and efficient rigging operations. A sample of the GUI is shown in Figure 2.

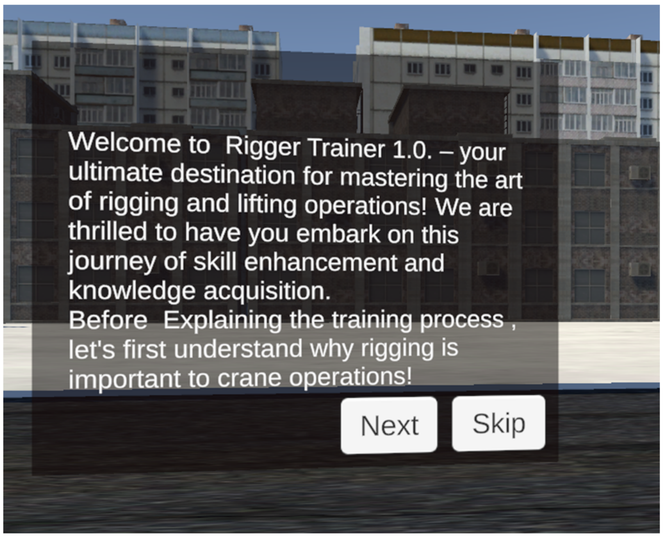

Fig. 3: The Introduction GUI.

3.2 Level 1 - Component Identification

At the outset of the VR training program, we prioritize establishing a strong foundation for trainees by focusing on providing a comprehensive understanding of the fundamental components that make up a rigging system. Through engaging 3D models and interactive hands-on exercises within the virtual environment, participants will delve into the intricacies of identifying key elements such as slings, shackles, hooks, and spreader bars. The VR experience offers a realistic and immersive environment, allowing trainees to explore lifelike representations of these vital components. By interacting with the 3D models, they will gain invaluable insights into the unique features and applications of each component. This in-depth comprehension is critical for ensuring safe and effective rigging practices in real-world scenarios. As trainees virtually manipulate the slings, shackles, hooks, and spreader bars, they will receive instant visual and auditory feedback, fostering a dynamic learning process. This hands-on approach within the VR environment enables them to internalize the knowledge effectively, bridging the gap between theory and practical application. By the end of Level 1, participants will have honed their ability to recognize and differentiate between various rigging components accurately. Equipped with this essential knowledge, they will be well-prepared to progress to Level 2, where they will practically assemble these components into basic rigging configurations, all while harnessing the power and potential of VR technology.

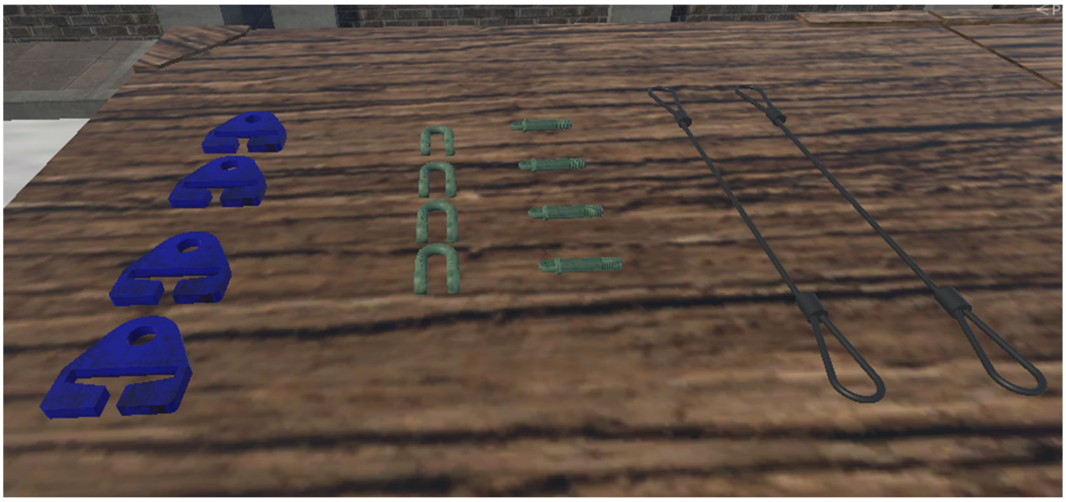

Fig.4 Rigging System Components

3.3. Level 2 - Basic Assembly and Secure Rigging

With a solid understanding of rigging components acquired in Level 1, trainees progress to Level 2, where they embark on the practical application of their knowledge in a virtual setting. In this stage, participants will immerse themselves in the VR environment to virtually practice creating various basic rigging assemblies, honing their skills in a risk-free and controlled space. Within the VR environment, trainees will have access to an array of virtual rigging components, including slings, shackles, hooks, and spreader bars, similar to what they encountered in Level 1 as can be seen in Figure 4.

They will have the freedom to select and manipulate these components to create different rigging configurations, such as single-leg slings, double-leg slings, and bridle slings. Real-Time Feedback: As trainees assemble the virtual rigging configurations, the VR system will provide real-time feedback on their actions. Visual indicators and audio cues will ensure that they correctly balance loads and securely fasten each component, enhancing their understanding of proper rigging techniques. This immediate feedback mechanism reinforces safe practices and encourages trainees to adjust until they achieve accurate rigging setups.

One of the feedback mechanisms used to enhance the learning process, is through highlighting the proper location of each component within the overall assembly as can be seen in Figure 5. This to ensure that the trainee would not require the aid of external factors and their learning journey would be self sufficient using the rigging training model only.

Fig. 5: Different Basic Rigging Assemblies

To enhance engagement and challenge trainees further, the VR program will introduce interactive challenges. These scenarios could include lifting differently shaped loads, coordinating multiple rigging components simultaneously. By navigating through these challenges, participants develop a deeper understanding of rigging complexities and learn to adapt their skills to diverse situations. Throughout Level 2, the VR training program follows a progressive approach, starting with simpler rigging configurations and gradually advancing to more complex setups. This gradual increase in difficulty ensures that trainees build their skills step-by-step, instilling confidence and proficiency in rigging operations.

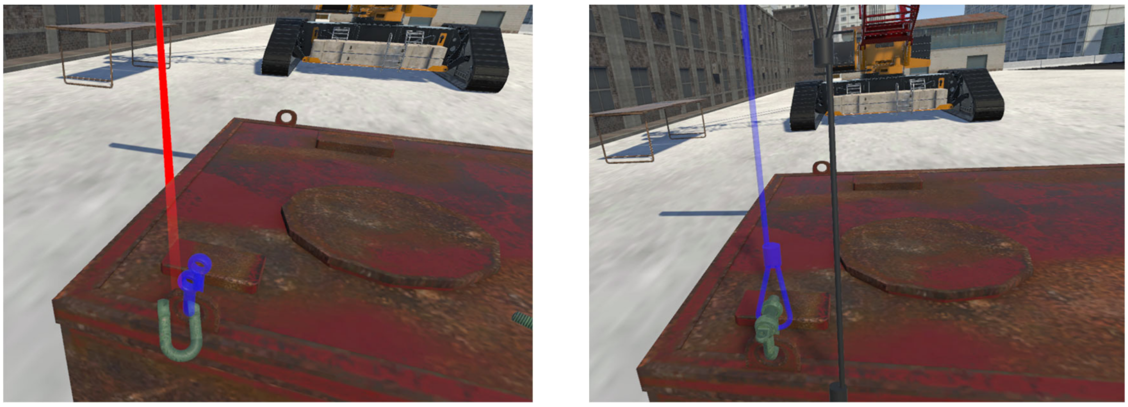

Fig.6: Training Feedback Mechanism

3.4. Level 3 - Advanced Assembly and Simulation

Level 3 represents the pinnacle of the VR Crane Rigging Training Program, where trainees are exposed to advanced rigging assembly exercises and sophisticated simulations. In this stage, participants take their skills to new heights as they tackle complex rigging scenarios, further solidifying their expertise and decision-making abilities.

In level 3, trainees are tasked with creating complete rigging modules from scratch within the virtual realm, similar to those shown in Figure 6. These modules involve intricate configurations and incorporate multiple components, without any guidance, applying what they learned in the previous levels. The VR environment provides an extensive library of rigging equipment, allowing trainees to experiment with various combinations to achieve the best setups.in some scenarios, the participants are not provided with the optimal component and are expected to produce rigging assemblies with the available components, preparing them for unpredictable scenarios in the field.

An integral part of level 3 enables trainees to evaluate the structural integrity and safety of their virtual rigging setups. After assembling and selecting a rigging configuration, a lifting simulation is used to assess the system's stability and provide immediate feedback on potential weaknesses or hazards. This invaluable feature allows trainees to identify and rectify errors.

Fig. 7: Different Advanced Rigging Assemblies

Through out the training process, the VR system records their performance metrics, allowing for detailed analysis and evaluation of their skills and decision-making capabilities. This data-driven approach enables trainers to identify areas of improvement and tailor further training to meet individual needs.

3.4. Level 3 - Advanced Assembly and Simulation

After developing the training procedure, a set of tests were done by the authors and other research team members at the University of Alberta to assess the effectiveness of the training and optimize the movement and interaction systems used throughout the training. Furthermore, the trainees were asked to choose which locomotion system was to be used when moving, and the teleportation movement system was deemed more user-friendly than continuous movement. Other concerns were tackled, and the overall quality was enhanced. In terms of interaction, some users had some difficulties getting used to the interaction system, but this issue was mitigated with more system usage.

Finally, the participants expressed that realistic graphics and environment improved their understanding and feeling of the tasks. However, they would eventually get fatigued when exposed to longer durations of using the model.

4. CONCLUSION

In conclusion, in this work, a framework for training inexperienced riggers using fully immersive VR was developed; the developed framework is expected to enhance the overall safety in crane-related operations as well as mitigate the number of incidents on construction sites that are caused by inadequate training, inappropriate rigging assemblies and human error. The expected improvements result from customizable and realistic training procedures that follow the health and safety regulations and the relevant training standards currently being used to train riggers and crane operators.

The framework performance was tested on a limited number of students and researchers with experience in crane-related operations. However, further plans to have a more extensive and detailed assessment of the performance of the training module are planned in the works to follow.

Furthermore, Future works include using other objective methods to further assess the developed model's validity. These objective methods would be used to provide a detailed comparison of the behavior of workers under training using VR and traditional methods—moreover, the measurement of vital signs to understand the impact of stress on their performance. This research can also be expanded on by creating a digital twin of the construction site and the rigging assemblies and then assessing the validity of the rigging assembly in real-time, allowing the workers to validate the lift in the virtual environment and modifying the actual assembly to minimize the possibility of an incident.

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